Second Annual Progress Report

PHYSICAL PROPERTIES OF MOLECULAR CLOUDS

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A. Introduction.

The results of this research grant during its second year are of increased significance and scope. During the first year, the primary emphasis was on heating mechanisms and H_2 abundances for diffuse clouds; first steps were also taken in the calculation of other molecular abundances. Building upon this work, far more extensive abundance calculations were carried out during this reporting period. Useful comparisons with observation were also made. Most important, time-dependent aspects of interstellar molecular abundances have been analyzed and important progress achieved in developing appropriate hydrodynamic methods for understanding the evolution of interstellar clouds.

The most significant result obtained this year was the demonstration that the conversion of carbon from C^+ to CO leads to thermal chemical instabilities which can influence the evolution of molecular clouds. In order to solve this problem, an integrated approach had to be employed which simultaneously treated chemical, ionization, thermal, and hydrodynamic effects. The astrophysical implications of this result are now beginning to be realized, and are of course under intensive investigation by our group.

Another noteworthy result relates to the very recent discovery of the formyl radical HCO in intermediate thickness interstellar clouds by Hollis and Snyder (AAS Bulletin 7, 540 (1975)). Although previous searches had been unsuccessful, these observers were led to try again on the basis of our abundance calculations of this molecule. These calculations provided the first estimates of the abundance of HCO using gas-phase ion-molecule reactions. The discovery of HCO, in connection with the detection of other radicals, supports the idea that ion-molecule reactions are important for the understanding of interstellar molecule abundances.

B. Research Progress.

1. C^+ - CO Transition in Interstellar Clouds - - The spatial aspects of the transition of carbon from CII to CO in interstellar clouds have been analyzed using the particular gas-phase ion-molecule reaction scheme initiated by the charge exchange reaction, $H^+ + O \rightarrow H + O^+$. Previous treatments had considered only radiative recombination as a destruction mechanism for C^+, and ignored molecule formation. The conditions for a molecular transition to occur are the presence of molecular hydrogen, cosmic ray production of H^+, and shielding of the CO-dissociating radiation. The characteristic thickness of the transition region was determined to be a hydrogen gas column density $N \sim 3 \times 10^{21}$ cm^{-2}, i.e. several magnitudes of visual extinction. Unpublished results of the Meudon group (P. Encrenaz et al) and the NASA GISS group (R. L. Dickman et al) provide observational confirmation of the qualitative results of this calculation. This work was recently published in the Astrophysical Journal (A. E. Glassgold and D. Langer, Ap. J. 197, 347 (1975)).

2. Molecular Abundance Calculations.

a. Abundance of Oxygen Bearing Molecules - - The final version of this work, previously reported in last year's annual report, has been finished and will be published in the May 15, 1976 issue of the Astrophysical Journal. In this calculation, the ionization and chemical balance of the following species were obtained for fixed steady state values of density n and temperature T: e; H^+, H_2^+, H_3^+; CI, CII; OI, OII, OH, OH^+, H_2O, H_2O^+, H_3O^+; CO, CO^+, HCO, HCO^+. The chemistry is based on gas phase ion-molecule reactions initiated by the slightly endothermic charge-exchange reaction, $H^+ + O \rightarrow H + O^+$. During the last year, new observations have become available on the abundance of OH and CO in diffuse clouds. These measurements are consistent with our calculated values and lend support to ion-molecule interstellar chemistry. The idea that diffuse clouds might provide suitable tests for molecule formation theories was the central motivation for this work, and this is now being confirmed by observations. (A. E. Glassgold and W. D. Langer).

b. The Discovery of the Formyl Radical HCO - - From our first work on oxygen-bearing molecules in the spring of 1974, we included both branches of the reaction

$$C^+ + H_2O \rightarrow \begin{matrix} HCO^+ + H \\ HCO + H^+. \end{matrix}$$

The upper branch had been mentioned by Klemperer as a means of producing HCO^+, when this molecule was still known as "X-ogen". Our objective was the calculation of CO abundances: HCO^+ leads to CO by dissociative recombination, for example, whereas HCO gives CO by photo dissociation. On the basis of our calculations, Hollis and Snyder were encouraged to search anew for the formyl radical and they made a positive detection on October 8, 1975 in several intermediate thickness clouds. The observed abundances of HCO and HCO^+ are in qualitative agreement with our theoretical estimates. This discovery provides important new support for ion-molecule chemistry in molecular clouds. (A. E. Glassgold and W. D. Langer).

c. Profiles of Molecular Abundances in Diffuse Clouds - - The above calculations are for fixed n and T, unlike our previous self-consistent calculations of molecular hydrogen (Ap. J. 193, 73 (1974)). Substantial progress was made during the last year in generalizing our earlier program to include the simpler oxygen-bearing molecules. Abundance calculations can now be carried out in which the effects of heating and cooling are simultaneously treated, along with chemistry and ionization and the attenuation of the interstellar UV field. Although further refinements in certain parts of the program are still required, several studies suggested by the OAO-C observations have been initiated. These include an analysis of clouds in which both HD and OH observations have been made, and the correlation between CI and CO measurements. (S. Federman and A. E. Glassgold).

3. Time Scales for Molecule Formation - - Relatively little attention has been paid to this problem in the past, largely because of uncertainty about how interstellar molecules are formed. In view of our increased understanding of ion-molecule reactions, we have investigated this question in some detail for the following types of chemistry: (1) O^+ charge exchange; (2) C^+ radiative association, and (3) H_3^+ reactions with O and C. The first dominates in warmer, diffuse clouds and the third in cooler, thicker clouds. By focusing attention on the slowest time-scales, i.e. making an adiabatic approximation for rapidly-equilibrating species, we were able to treat the problem in closed form in terms of relatively simple nonlinear differential equations. It was determined that most members of the OH and CO families of molecules equilibrate rapidly, except for CO - - the most abundant heavy molecule. The next slowest are the neutral species OH and H_2O, and CH, CH_2, C_2H, and C_2. The time required to form CO can range from 2×10^5 to 2×10^6 y, depending on the physical conditions of the cloud. The longest times are associated with the Herbst-Klemperer H_3^+ chemistry. Because dynamical times for clouds can be as short as 10^6 y, there may well be situations where the usual steady-state hypothesis for molecular abundances is inapplicable. A manuscript of this work has been drafted, and is being put into final form. (A. E. Glassgold and W. D. Langer).

4. Thermal-Chemical Instabilities in CO Clouds - - Although the importance of CO as a coolant for molecular clouds has been recognized for some time, the effects of a varying CO abundance have been ignored. That such effects can be of considerable importance may be understood from the fact that lowering the temperature by cooling generally leads to higher densities. But increased density promotes the formation of CO, and so the conditions for a "runaway" are set. We have made a systematic analysis of this possibility using an appropriate generalization of Field's work on thermal instability. The analysis is based on a linearization of the equations of hydrodynamics extended to include the cooling by CO as well as by C^+ and the formation and destruction mechanisms for CO. The latter may be described roughly in terms of two ion-molecule schemes, the O^+ charge-exchange and the C^+ radiative-association chemistries. A new instability condition was derived:

$$\lambda_p = \frac{1}{c_p}\left[\left(\frac{\partial \mathcal{L}}{\partial T}\right)_{p,x} + \mathcal{L}_x \left(\frac{\partial x}{\partial T}\right)_p\right] < 0 ,$$

where c_p is the heat capacity at constant pressure, x is the zero order, e.g. steady state CO abundance, and $\mathcal{L}$ is the (net energy) loss function of the medium. The quantity λ_p is a characteristic thermal-chemical time-scale parameter (units s^{-1}). We have found that relatively diffuse clouds (a few visual magnitudes thick) are unstable with respect to conversion of carbon from C^+ to CO, with

a characteristic time in the range $2 \times 10^5 - 10^6$ y. These and related results may be expected to be important in the evolution of interstellar clouds; for understanding the space-time fluctuations of the molecular cloud gas; and as a mechanism for "thermal-chemical" fragmentation of clouds and the formation of pre-protostellar objects. A first brief report of this work will be published in the March 1, 1976 issue of the Astrophysical Journal. (A. E. Glassgold and W. D. Langer).

5. Non-Ionizing Radiation and Interstellar Clouds - - Ninety percent of the total radiative energy in the interstellar medium is in the form of non-ionizing radiation. Usually this radiation is assumed to be very weakly coupled to other components of the interstellar medium. We have proposed that the photodesorption of molecules and atoms from the surfaces of interstellar dust grains may couple the radiation field and the gas-dust component of interstellar clouds. Recent progress in the physics of solid surfaces lends support to this idea. This process can have a high efficiency for separating gas and dust, and may also be effective in heating clouds. In addition to investigating the inhomogeneous dust distribution of diffuse clouds, we have analyzed the stability of the surface of denser clouds contained by radiation pressure. Radial instabilities are predicted by the linear theory. This mechanism is of interest for the fragmentation of interstellar clouds and subsequent star formation. The formation of a star inside a cloud may, for example, trigger further fragmentation and star formation. A first report on this work will be published in the June 1, 1976 issue of the Astrophysical Journal. (H. Gerola).

6. Hydrodynamics of Interstellar Cloud Evolution - - The first steps in the development of a hydrodynamical program for studying cloud evolution have been taken. The objective is to carry out such studies incorporating new physical effects mainly associated with the interstellar molecules. This is completely new ground, because the chemistry and thermal effects of interstellar effects have never been studied before in a hydrodynamic program. (The most closely related research is the instability analysis of CO clouds reported above.) A satisfactory Lagranian integration scheme has been developed for the mass and momentum equations. The numerical problems connected with the chemistry and the loss function $\mathcal{L}$ are now being dealt with.(H. Gerola and A. E. Glassgold).

7. Generalization of the Jeans Instability - - The condition for stability of a molecular cloud has been generalized to include the following effects: gravity, gain and loss of energy, heat conduction, and chemical evolution. The new condition is

$$c^2k^2(\lambda_p + D_p k^2) - \tau_J^{-2}(\lambda_\rho + D_\rho k^2) < 0,$$

where k is the wave number of the instability, c is the adiabatic sound speed, λ_i ($i = p,\rho$) are characteristic thermal-chemical

time-scale parameters, D_i are diffusion constants, and $\tau_J = (4\pi G\rho)^{-\frac{1}{2}}$ is the familiar Jeans time. This result should be useful for understanding the evolution of interstellar clouds whose density is such that the Jeans time is comparable or somewhat longer than the thermal-chemical times. For example, if a cloud is thermal-chemically stable (λ_p, $\lambda_\rho > 0$), the Jeans length and mass are decreased by the first and third powers of the ratio $(\lambda_p/\lambda_\rho)^{\frac{1}{2}}$. Because $\lambda_p/\lambda_\rho < 1$ (sometimes $\ll 1$), this implies that the thermal and chemical effects promote or initiate the gravitational instability. (A. E. Glassgold).

C. Scientific Staff.

Dr. A. E. Glassgold, Principal Investigator
Dr. H. Gerola, Postdoctoral Research Scientist
Mr. S. Federman, Graduate Student

D. Publications and Talks.

PUBLICATIONS*

1. A. E. Glassgold and W. D. Langer, "Model Calculations for Diffuse Molecular Clouds", Ap. J. 193, 73 (1974).

2. A. E. Glassgold and W. D. Langer, "C^+-CO Transition in Interstellar Clouds", Ap. J. 197, 347 (1975).

3. A. E. Glassgold and W. D. Langer, "Thermal-Chemical Instabilities in CO Clouds", Ap. J., March 1, 1976.

4. A. E. Glassgold and W. D. Langer, "Abundance of Simple Oxygen-Bearing Molecules and Ions in Interstellar Clouds", Ap. J., May 15, 1976.

5. H. Gerola and R. A. Schwartz, "Enhanced Effects of Starlight in the Interstellar Medium", Ap. J., June 1, 1976.

6. A. E. Glassgold and W. D. Langer, "Time Scales for Molecule Formation by Ion-Molecule Reactions" (in preparation).

TALKS AND VISITS

1. Informal meeting with the Princeton OAO-C group, November 15, 1974 (A. E. Glassgold and W. D. Langer).

2. "Effects of Thermal Diffusion on the Helium Line Intensities in the Solar Transition Region", invited paper at the Solar Physics Division meeting of the AAS, Boulder, Colorado, January 19-23, 1975 (H. Gerola).

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* Publication 1 is not discussed above in Section B because it was research carried out entirely in the previous year and discussed in the First Annual Progress Report.

3. "Problems of Star Formation", seminar at the University of South Carolina, February 13, 1975 (H. Gerola).

4. "C^+-CO Transition in Molecular Clouds", paper read at 145th meeting of the AAS, Bloomington, Indiana, March 26, 1975 (BAAS 7, 264, 1975) (A. E. Glassgold).

5. Institute of Astronomy, University of Cambridge, July 6 - August 1, 1975 (A. E. Glassgold).

6. "Thermal Properties and Stability of Molecular Clouds", invited paper, Workshop on Interstellar Molecules, Meudon, France, August 19, 1975 (A. E. Glassgold).

7. "Thermal Instability of Interstellar Clouds", seminar Groningen Observatory, Netherlands, September 2, 1975 (A. E. Glassgold).

8. "Thermal Instability of Interstellar Clouds", seminar Leiden Observatory, Netherlands, September 4, 1975 (A. E. Glassgold).

9. "Thermal Properties and Stability of Molecular Clouds", two seminars at New York University, September 8 and 15, 1975 (A. E. Glassgold).

10. Neighborhood meeting at Center for Astrophysics, Harvard University, October 30, 31, 1975 (H. Gerola and A. E. Glassgold).